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THE PETROLOGY OF THE MIOCENE SEDIMENTS OF THE AURE TROUGH, PAPUA

by A. B. EDWARDS, D.Sc., Ph.D., D.I.C.

[Read 10 July 1947]

Abstract

The Miocene strata of the Aure Trough consist of about 15,000 feet of greywackes and mudstones, in about equal proportions, with minor intercalations of grit, conglomerate and limestone. They contain an abundant fauna of marine microfossils, together with abundant plant fragments, and the remains of a fossil turtle. The greywackes are ill-sorted rocks that show prominent graded bedding, and occasional slump structures. They consist essentially of angular grains of basic plagioclase, hornblende and pyroxene, with minor amounts of other minerals, together with numerous rounded rock fragments in a prominent clay matrix. The rock fragments consist largely of a variety of andesites, together with fragments of schist, mudstone, reef quartz, and other rock types. The majority of the mineral grains and rock fragments are fresh, but every thin section reveals a proportion that are weathered to varying degree. The mineral grains closely resemble those of Tertiary andesitic lavas in adjacent parts of New Guinea, and the andesite fragments can be matched with these rocks. Both greywackes and mudstones closely approximate the average andesite in chemical composition. They appear to be derived from a mountainous terrain, by the erosion of wide-spread andesitic tuffs, under climatic conditions similar to those now prevailing in the area; and they were deposited in still, moderately deep water (within the neritic zone), free from all but weak current action, and close to a shore line. Deposition was probably accompanied by subsidence of the floor of the receiving area.

In naming the rocks, emphasis has been placed upon processes of sedimentation rather than on the composition of the sediments. On this basis the rocks are *greywackes* as defined by Pettijohn and by Fischer, and are classified as such.

Introduction

This petrological study of the Miocene sediments of the Aure Trough, Papua, is based upon the examination of a suite of representative specimens supplied by the Australasian Petroleum Co. Ltd. It was undertaken as part of the programme of the Mineragraphic Section of the Council for Scientific and Industrial Research (Mineragraphic Report No. 349, January 1947), and is published here by permission of the Council and of the Company. My thanks are due to Dr. M. F. Glaessner, Mr. J. N. Montgomery and Mr. G. A. V. Stanley, of the Australasian Petroleum Co. for providing detailed information as to the field occurrence of the sediments, and for constructive criticism of the manuscript. The specimens were collected chiefly by Mr. Stanley.

The Upper Tertiary (Miocene and Pliocene) sediments of New Guinea occur within two elongated, north-westerly trending basins, extending along either flank of the Central Highlands (Beltz, 1944) (Fig. 1). A connection between these two basins is envisaged at their south-eastern ends, in the area between the Watut and the Upper Ramu Rivers (Fisher, 1944). This connection, if it existed, opened southwards into a deep transverse trough, known as the Aure trough, across the more southerly basin. It is from this trough that the rocks under consideration were obtained.

The Miocene strata in the Aure Trough are stated to have a maximum thickness of about 15,000 ft., and to overlie unconformably a complex that includes metamorphosed sediments, Jurassic and Cretaceous limestones, shales, sandstones and conglomerates, and locally, Eocene shales, limestones and grits, as well as a variety of igneous rocks of various ages.

The Miocene sediments are reported to consist of sandstones and mudstones or shales, in about equal proportions. In places the sandstones and mudstones alternate rapidly, but elsewhere they occur in massive formations, several hundred feet thick. The sandstones, which include thick gritty members have been referred to variously as greywacke, and as tuffaceous sandstones. They carry an abundant fauna of marine microfossils. These are characteristically pelagic but some benthonic forms occur. Beds of shelly fossils have been found, but they are rare and local. Corals occur, but only as occasional, isolated, stunted, single growths. In addition, fragmental plant remains, mostly carbonized wood fragments (fusain ?), occur abundantly in the bedding planes of most of the sandy members. The remains of a fossil turtle have been found near the mouth of Kariava Creek (Glaessner, 1942).

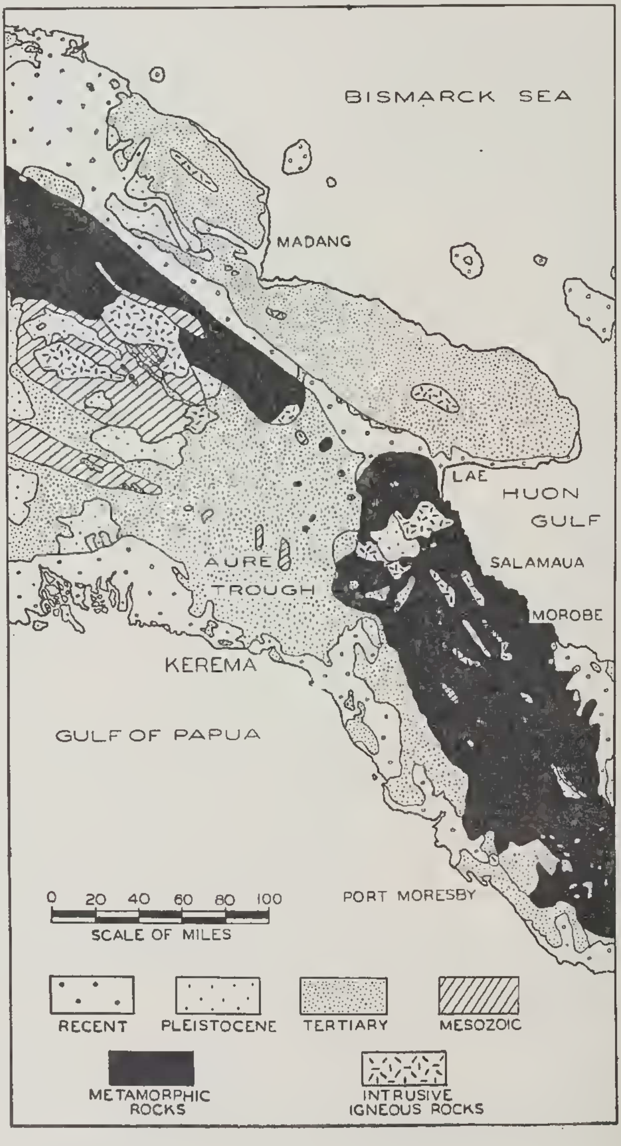

Fig. 1. Geological Sketch Map of the eastern part of New Guinea, showing the location of the Aure Trough. (Geology supplied by the Australasian Petroleum Co. Ltd.)

The sandstone members are characterized by *graded bedding* and current bedding is unusual, though well-developed current bedding has been observed at an occasional locality. Current bedding is not evident in any of the sandstone specimens examined, but most of the finer-grained sandy shales examined show small scale current bedding indicating that such currents as affected the sediments during deposition were generally strong enough to move only the finer-sized particles. Bedding is apparent in hand specimens of the finer-grained sandstones, being marked by dark bands, 0·1 mm. to 1·0 mm. thick. In thin sections these dark bands are seen to contain rather more clay matrix than the adjacent lighter bands. More rarely a thin dark band corresponds to a concentration of grains of magnetite and ilmenite. In several instances the beds show micro-grading. One specimen showed graded bedding extending through a thickness of about 8 cm.

Bedding is not often apparent in the coarser sediments, but the thin sections reveal that in some, many elongated particles tend to lie with their long axes parallel, giving a rude bedding. This can also be seen in polished surfaces of the coarser, gritty rocks.

Occasional specimens of fine-grained sandstone, or sandy shale, show evidence of contemporaneous erosion. Saucer-shaped hollows, a centimetre or so deep, and several centimetres across, have been eroded in the finely bedded shale, and filled with distinctly coarser-grained sand, that overlaps the truncated edges of the shale beds. The upper surface of the sand filling is flat, so that the sand ' bed ' is plano-convex in shape, and is conformably overlain by further finely-bedded sandy shales. Further evidence of occasional contemporaneous erosion is provided by the occurrence of intraformational conglomerates, in which the pebbles consist of more or less well-rounded fragments of mudstone, set in a normal sandstone matrix (Plate XII, Fig. 1).

Ripple markings are rare, but have been observed in places, and one specimen of mudstone has been obtained bearing impressions that resemble runnel markings, suggesting local exposure during deposition. No other evidence suggesting exposure during deposition is known ; and the mineral composition of the sandstones is such that they must have been buried rapidly to preserve the fresh condition of the many chemically unstable mineral grains present.

Slip bedding and slump structures are not uncommon in the mudstones where thinly bedded and, in places, a mudstone bed has been broken into a series of discontinuous, irregular-shaped fragments, now interbedded in greywacke. Several of the specimens examined contain irregular fragments of mudstone, which may have been formed in this way. It would be difficult to explain otherwise the penetration of the greywacke material into fractures in the angular mudstone fragments. It is possible that the intraformational conglomerates may have developed by attrition and re-burial of mudstone fragments formed in this way.

Syngenetic concretions, presumably calcareous, in view of the abundant calcite in some specimens, are found locally in the sandstones. They are generally small, not exceeding 6 in. in diameter.

Conglomerates, with cobbles up to 6 in. in diameter, are developed locally ; they occur as thick strongly lensed beds of no great volume. The cobbles, in so far as they have been examined, are well rounded, and consist of hard rocks, chiefly andesites, with occasional pebbles of quartz diorite, granophyre, reef quartz, schist, and rarely, Eocene limestone. A number of cobbles of similar size and shape, taken in the stream beds, but not in situ, have also been examined. These may well be derived from eroded Aure conglomerates, and include the following types : hornblende granodiorite, syenite, hornblende andesite, hornblende dacite, hornblende dolerite (diorite), dacite tuff, volcanic agglomerate, and nodular graphitic schist—all rocks that have been found as fragments in the greywackes. A fine-grained conglomerate (or coarse grit) UV.388 from the Dude section (see below) yielded well rounded pebbles of augite andesite, hornblende andesite, graphitic schist, volcanic agglomerate, sandstone, quartzite, shale, basaltic or andesitic glass, altered (?) basalt, and hornblende granite (Plate XII, Fig. 2).

Widespread, but very thin beds of marly limestone, rarely more than a few inches thick, occur throughout the sequence, but constitute a negligible thickness of the sedimentary series. These so-called Puri limestones contain abundant micro-fossils, chiefly foraminifera. At one locality a detrital limestone, up to 20 feet thick, has been reported to occur.

No igneous rocks are known to occur within the series.

The specimens on which the following petrological study is based came from three sections. Two are sections of the basal Upper Miocene : (1) the Cupola section, about five and a half miles south-east of Kerema (Fig 1), where a thickness of more than 3000 ft. of sediments is exposed, containing three thick sandstone horizons (Fig. 2). (2) the Auivera and Napere Creek section, 23 miles north-west of Kerema, where another 3000 ft. thickness of sediments is exposed. This section includes four thick sandstone horizons, that have been termed the Murakawarra, the Beoke, the Ouka and the Napere sandstones, in descending succession (Fig. 2). The third section is the Dude section, in

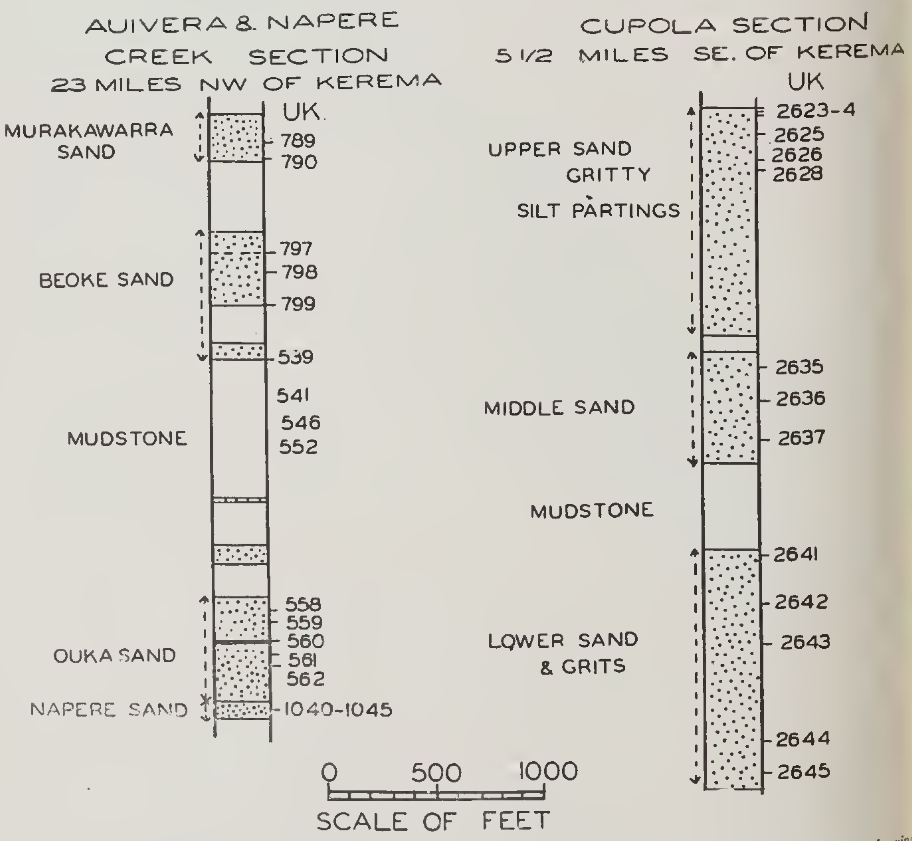

Fig. 2. Stratigraphical Columns of the Aurivera and Napere Creek Section (2A) and the Cupola Section (2B), showing the relative positions of the specimens examined. (UK 789, etc.)

Wommgo Creek, about 26 miles north-north-west of Kerema, and consists of sandstones about 200 ft. thick underlying beds that contain Middle Miocene foraminifera. The specimens from the two thick sections are referred to by the UK. series of numbers and their relative stratigraphic positions are indicated in Fig. 2. The specimens from the Dude section are referred to by the UV. series of numbers. The numbers refer to the field localities in the records of the Australasian Petroleum Company.

Apart from the limestones, conglomerate pebbles, and the more calcified specimens, the rocks examined were too friable to withstand grinding as received. To prepare thin sections it was necessary to impregnate them with canada balsam. Blocks from each specimen were immersed in a warm, tenuous solution of canada balsam in xylol, and then evacuated with a hand pump. They were kept in this condition for an hour, or until on further evacuation no more bubbles were emitted. The blocks were then removed from the solution and dried at about 35°C for a week. On grinding to prepare a surface for mounting it was generally necessary to re-impregnate the ground surface once or twice with the canada balsam solution, and dry overnight, at each stage of grinding, before a satisfactorily plane surface was obtained. Many of the specimens required further impregnation immediately preceding the final stage of grinding of the thin section, to prevent grains tearing out before the requisite thinness was reached. About 35 specimens were sectioned, two or more sections being cut from most specimens.

Greywackes (1)

The typical greywacke of the Napere Creek and Dude sections is a sandy friable rock, grey to brownish on exposed surfaces but dark grey when freshly broken. It is poorly sorted, the grains ranging in diameter from about 2·5 mm. down to clay particles, with about 25 to 30 per cent of the rock composed of particles less than 0·05 mm. in diameter. The occasional large grains consist chiefly of sub-angular to rounded rock fragments, and scattered angular crystals of clear felspar. The hand specimens have a uniform appearance, apart from occasional dark, somewhat cellular patches, up to 2 cm. across, that consist of clots of coarse felspar crystals, loosely cemented together by limonitic material. The Ouka greywacke is somewhat coarser-grained, but equally ill-sorted. The Beoke and Murakawarra greywackes are rather finer-grained, and some of the Beoke specimens show fine bedding. Occasional specimens have weathered margins, which are stained brown with limonite, but most show little or no sign of weathering.

The greywackes from the Cupola section are coarser-grained and lighter in colour. They range from medium-grained to extremely poorly sorted gritty sandstones, in which particles or rock fragments in excess of 2·5 mm. diameter constitute more than 5 per cent of the rock. The abundant rock fragments are commonly black or greenish black, and the coarser felspars appear white, so that the rocks have a speckled appearance. A large proportion of the rock fragments are elongate, and tend to lie with their long axes parallel so that the rock has the appearance of incipient bedding.

THIN SECTIONS

Examination of thin sections reveals that the greywackes are a very homogeneous group of sediments of unusual composition. They consist essentially of angular grains of plagioclase and hornblende, with varying proportions of

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(1) The sandstone members of the Aure sediments can be described either as greywackes, tuffaceous sandstones, or tuffs, according to the mode of origin ascribed to them. The choice of the term greywacke, and the sense in which it is used, is explained in the sections on the origin of the sediments, and on nomenclature, with which the report is concluded.

rounded to angular fragments of igneous and sedimentary rocks, set in a prominent clay matrix, and are very poorly sorted. Their texture in thin section could be described as that of a micro-breccia (Plate XIII, Figs. 2, 4). Quartz, apart from fragments of reef quartz, or of quartzite or other sedimentary rock containing quartz, is notably lacking. In the greywackes from the Cupola section it generally constitutes less than 5 per cent of the rock, and in those from the other sections it is almost absent. Pyroxenes are generally a minor component, but in some groups of specimens they are almost as abundant as hornblende. Other minerals present in minor amounts are magnetite, ilmenite, leucoxene, limonite, biotite, muscovite, perthite (or orthoclase), epidote, glauconite (?), garnet, tourmaline, zircon and corundum. Carbonate minerals, chiefly calcite, are invariably present, sometimes in abundance. Most of the calcite is authigenic, but some occurs as the tests of foraminifera, which are present in every section, and as very occasional corals. The chief differences are in the relative proportions of the various components present (Table 1), and in the range of grain size (Table 2).

The plagioclase is for the most part clear and fresh, but in every slide occasional grains or parts of grains are clouded, with alteration to sericite or, more commonly, to kaolin. In many instances the fresh plagioclase has been partly replaced by calcite, the calcite tending to replace the more calcic zones and cores of the crystals, which are often strongly zoned. The individual felspar grains are mostly angular, some extremely so, often with crystal faces forming some of the boundaries. Occasional grains preserve complete crystal form, and some show embayed rather than fractured margins, with curved re-entrants. Most grains, however, are bounded by one or more fracture surfaces. As a result the shape of the plagioclase grains varies considerably, with a tendency for a stumpy prismatic form to prevail. The plagioclase shows prominent lamellar twinning and zoning, some grains showing oscillatory and reverse zoning. The free grains closely resemble the plagioclase phenocrysts in some of the andesitic fragments that are abundant in the rock, and can be matched also with the plagioclase phenocrysts in many of the andesites of New Guinea and the adjacent islands to the east. The composition of the grains cannot always be established but generally the cores of the crystals consist of labradorite, grading to andesine in the outer zones, in some instances with a narrow rim of more alkalic felspar. Some grains, on the contrary, have rims of clear calcic plagioclase enclosing an irregular core of somewhat altered, more sodic plagioclase of distinctly lower refractive index.

Orthoclase is a rare constitutent, and is lacking from most of the rocks. It is present in small amounts, however, in the coarser, gritty sandstones of the Cupola section, where it is associated with fragments of granite and syenite(?). It generally contains a proportion of ex-solution perthite.

The hornblende occurs as angular or prismatic grains. Many are fragments of larger grains, but a number retain their crystal outline. Many grains are fresh and unaltered, but some show alteration around their margins and along cleavages. The proportion of hornblende grains so altered is notably higher than the relative proportion of altered felspars. The most common alteration is a replacement by calcite, which invades the hornblende along the cleavage planes, and finally reduces it to a calcite pseudomorph. Many of the grains have a rim of 'welded' magnetite granules. This is a product of a reaction with a magma, or the volatiles of the magma, during crystallization or extrusion, and can be matched with the hornblende phenocrysts in the andesitic fragments in the rock, as well as with hornblende phenocrysts in New Guinea andesite lavas. In a number of grains, however, this primary magnetite rim has been altered to limonite, as a result of weathering. The fact that the alteration of the

TABLE I.

MICROMETRIC ANALYSES OF AURE GREYWACKES

Constituents	1	2	3	4	5	6	7	8	9	10	11	12	13
Quartz	0·1	0·1	0·2	0·1	tr.	tr.	tr.	3·1	5·5	3·5	7·5	8·1	2·5
Felspar*	30·6	25·7	32·2	24·3	23·5	29·2	21·8	8·5	10·3	15·7	25·8	10·0	22·0
Hornblende** ..	11·9	7·5	7·2	5·5	5·5	8·3	5·2	5·4	4·4	5·7	13·8	4·3	4·7
Pyroxene***	tr.	tr.	3·3	3·7	0·3	0·8	1·1	1·1	1·5†	1·6	0·9	0·4	4·0
Igneous fragments ..	5·5	4·5	20·0	28·2	25·5	15·8	34·3	30·3	30·5	29·5	9·3	21·1	22·0
Sedimentary fragments	1·3	1·2	3·5	2·4	3·7	4·2	5·0	20·0	24·3	11·9	11·5	22·1	10·9
Matrix	50·6	61·0	33·6	35·7	41·5	41·7	31·6	32·6	23·5	32·1	31·2	34·0	33·9

* chiefly plagioclase **plus magnetite, ilmenite, magnetite pseudomorphs and calcite pseudomorphs after hornblende.

*** plus biotite (generally negligible) † chiefly biotite

Explanation :

1. UK.1041, Napere sandstone.
2. UK.1042, Napere sandstone.
3. UK.559, Ouka sandstone.
4. UK.562, Ouka sandstone.
5. UK.799, Beoke sandstone.
6. UK.797, Beoke sandstone.
7. UK.790, Murakawarra sandstone.
8. UK.2623, Upper sandstone, Cupola section.
9. UK.2625, Upper sandstone, Cupola section.
10. UK.2636, Middle sandstone, Cupola section.
11. UK.2644, Lower sandstone, Cupola section.
12. UK.2642, Lower sandstone, Cupola section.
13. UV.381, Dude section.

TABLE 2

SIZING ANALYSES OF AURE GREYWACKES

British Standard Screen (Mesh)	Aperture mm.	1	2	3	4	5	6	7	8
over 7	2·41	—	0·2	—	—	—	5·7	—	—
7-10	1·67	0·2	0·2	—	—	—	3·8	—	—
10-14	1·20	0·4	0·6	—	0·6	0·1	4·2	—	0·5
14-18	0·85	0·7	1·3	0·8	1·5	0·3	3·8	1·2	2·2
18-25	0·60	2·5	3·1	6·4	3·5	1·2	5·1	5·8	7·6
25-36	0·421	7·2	6·6	13·8	5·5	3·3	6·1	10·9	11·0
36-52	0·295	12·7	11·1	14·8	6·5	7·0	6·7	14·8	10·8
52-72	0·211	16·6	14·8	13·8	8·3	12·7	7·2	15·3	10·3
72-100	0·152	13·6	13·0	11·1	11·9	14·4	6·9	12·7	8·9
100-150	0·105	10·1	10·2	8·4	12·3	13·7	6·9	9·0	7·7
150-200	0·076	6·4	7·2	5·8	11·5	11·9	6·8	5·9	6·7
200-300	0·053	3·5	3·6	2·7	5·4	6·9	4·0	3·1	4·0
under 300	—	26·1	28·1	22·4	33·0	28·4	32·8	21·3	30·3

1. UK.1040, Napere sandstone.
2. UK.1041, Napere sandstone.
3. UK. 562, Ouka sandstone.
4. UK. 797, Beoke sandstone.
5. UK. 789, Murakawarra sandstone.
6. UK.2623, Upper sandstone (gritty), Cupola section.
7. UK.2636, Middle sandstone, Cupola section.
8. UV.381, sandstone, Dude section.

hornblende grains to limonite is restricted to occasional grains indicates that the altered grains suffered weathering before deposition in the present rock. Some grains have altered to chlorite or to epidote.

Several varieties of hornblende are present in every section. They are distinguished chiefly by their colour. One variety is common brown hornblende, pleochroic from straw yellow to brown. A second is pleochroic from pale green to brown. More striking is a variety of oxy-hornblende (basaltic hornblende) pleochroic from foxy-red to golden brown, and with almost straight extinction. All three varieties can be matched with the hornblende phenocrysts of the andesite fragments in the rocks, and with hornblende phenocrysts in New Guinea andesites. The foxy-red variety is presumably a form derived from the more common brown form by oxidation during extrusion, at a temperature above 750°C and is, in a sense, the hornblende equivalent of iddingsite. It almost always has a rim of magnetite granules, marking the further stage in oxidation of its iron content ; and in extreme cases, is completely converted to a magnetite pseudomorph, often hollow.

Less common is an occasional grain of hornblende pleochroic from deep green to pale green, occurring as sheaf-like aggregates, with no well defined crystal outline. This hornblende bears a resemblance to that of amphibolites. Still less common are grains of an amphibole that is pleochroic from deep green to blue-green and bears some resemblance to glaucophane.

Pyroxene is a relatively uncommon mineral in most of the greywackes, but in some, notably the Dude sandstone UV.381 and the Ouka sandstone UK.560-562, it approximates in abundance to the hornblende. Three varieties of pyroxene have been observed. The most common, which occurs in every section, and is much the most abundant in the greywackes which contain a notable amount of pyroxene, is a faintly pleochroic, pale greenish-brown augite, with a high refractive index, a large extinction angle, and 2V about 60°, suggesting that it is a ferriferous augite. It occurs as angular fragments, and is generally fresh, but occasional grains show partial alteration to calcite, generally around the margin and along cleavages. Very occasionally it shows alteration to limonite. Some grains contain clouds of small dark inclusions but most are quite clear.

A second, less common variety is colourless and has a lower refractive index. It also is an augite, with a large extinction angle, and 2V about 60°. The third variety, which occurs only as very occasional grains, is a hypersthene, showing straight extinction, and pleochroism from pale green to palest pink.

Biotite is always present, but generally only as occasional flakes. In occasional specimens, however, particularly UK.2625, from the Upper Sandstone of the Cupola section, it amounts to about 1·5 per cent of the total rock. It is distinctly more abundant in these gritty sandstones than in the more even grained greywackes. The flakes are commonly crumpled or twisted; and there is a common tendency for calcite to crystallize as lenses in the cleavage planes of the flakes, opening them out, and fraying them. Most of the biotite is fresh, but occasional grains are bleached.

Muscovite is not a prominent mineral in the greywackes, but is present occasionally as small flakes.

Quartz becomes more abundant with increasing grain size of the greywackes, and is most abundant in the gritty members. This is probably related to the relative abundance of fragments of reef quartz, coarse-grained quartzite, and granite in these rocks.

Chlorite occurs as occasional vermiform intergrowths in the quartz, as an alteration product of the several ferro-magnesian minerals, and in some specimens as part of the matrix. It is never very abundant, however. Resembling it are occasional bright green grains of glauconite(?). Epidote, characteristically pleochroic from yellow to colourless, is associated with the chlorite in some instances, and is generally associated with altered ferro-magnesian grains, principally the hornblende.

Magnetite and ilmenite occur as minute granules and as sparsely distributed detrital grains. In some, the ilmenite can be seen to occur as a network of laths in the cleavage directions of the magnetite. Some grains are quite fresh, others show more or less complete alteration to leucoxene. In addition to magnetite occurring in this way, there is a considerable proportion of finely granular magnetite occurring as rims and pseudomorphs after hornblende crystals.

Apatite occurs as occasional, relatively coarse, grains in most slides, and some sections contain an occasional grain of tourmaline.

AUTHIGENIC MINERALS

In addition to the detrital minerals, several authigenic minerals are found in varying degree in most of the greywackes. These include calcite, epidote, pyrite (or other iron sulphides), and chlorite.

The calcite is much the most common. It is present in every section, generally constituting several per cent of the rock. In the more heavily carbonated rock it may constitute more than 15% of the total (Table 4, Analysis No. 2). When present in small amounts it shows a preference for replacing the calcic plagioclase and the hornblende crystals; but when present in abundance it replaces a considerable proportion of the matrix. The fresh condition of the rock and the replacing habit of the calcite leave no doubt that it was introduced during diagenesis.

The epidote is a minor constituent of the rocks, and occurs chiefly where calcite or chlorite has replaced hornblende, as a product of the replacement. It is pleochroic from colourless to lemon yellow, with characteristically high polarisation colours.

Iron sulphide minerals (pyrite, marcasite and pyrrhotite) have been observed in various thin sections. They tend to replace the groundmass or the felspar grains, and usually have very irregular shape. Some grains, from their bronzy colour in reflected light, resemble pyrrhotite ; others are greyer, and consist of pyrite or, more probably, marcasite.

Chlorite occurs partly as a replacement of ferromagnesian minerals, and partly as irregular interstitial patches in the matrix. This latter chlorite is presumed to be of authigenic origin, deposited as a cement material during compaction of the rocks. The proportion of it is relatively small compared to the proportion of matrix.

Heavy Mineral Constituents

The heavy mineral constituents were extracted by suspension of the sized fractions of the several specimens in acetylene tetrabromide (tetrabromethane) of sp. gr. 2.90, after cleaning by immersion in cold 50% hydrochloric acid, which dissolved any carbonate. Treatment of a series of sized fractions from a 100 gram sample of UK.2636 (Cupola section, middle greywacke formation) showed that the heavy minerals other than hornblende, pyroxene, biotite, epidote and chlorite, were concentrated in the 150-200 mesh and 200-300 mesh fractions. This was confirmed by a similar examination of the sized fractions of UK.1041; and was to be expected in view of the small size of the heavy accessory minerals of most igneous and sedimentary rocks. In the other specimens, examination for heavy minerals was limited to the 150-200 mesh fraction. In each case the heavy mineral concentrate was divided into a strongly magnetic fraction, a feebly magnetic fraction and a non-magnetic fraction. These were mounted separately.

The strongly magnetic fractions contained most of the hornblende and iron ores, with a proportion of the pyroxene and biotite, and in every sample, a little pink garnet. The hornblende and pyroxene fragments were always angular, though some showed some sign of water wear. The iron ore grains, by contrast, included a number that were well rounded. The garnet occurred partly as irregular angular fragments, and partly as water-worn grains, few of which, however, were well rounded. There was notably less garnet in the two pyroxene-rich greywackes (the Ouka, UK.562, and the Dude, UV.381) than in the pyroxene-poor rocks. The fine-grained greywackes (the Beoke, UK.797, and the Murakawarra, UK.789) appeared to contain most garnet. Some samples contained a little tourmaline.

The feebly magnetic portions consisted chiefly of pyroxene and hornblende, with some iron ore, most of the epidote, which was always angular, some bleached biotite, and some chlorite. In addition it contained a proportion of the leucoxene, commonly as rounded grains, an occasional grain of tourmaline, either blue or brown, and a fragment or two of apatite.

The non-magnetic fraction contained the plagioclase impurities, some pyroxene, hornblende, bleached biotite, epidote—all as angular fragments, and in addition zircons, apatites, an occasional tourmaline, an occasional rutile grain, and some leucoxene and chlorite. In the finer grained greywackes (Beoke, UK.797, and Murakawarra, UK.789) and in the Napere greywacke (UK.1041) there was an abundance of iron sulphides in crystals, irregular masses, and globular clusters. Some had the brownish reflection colour of pyrrhotite, and some a yellow reflection colour suggestive of chalcopyrite. Most of it, however, was greyish to brassy, suggestive of pyrite or possibly marcasite.

Two varieties of zircon were present in each sample, a pink zircon with inclusions, and a colourless zircon with, or without, inclusions. The pink zircon almost always occurred as double-ended crystals, or fragments of such, showing little or no wear. The colourless zircons, on the contrary, were commonly well rounded, and some approached a spherical shape. It can be assumed that the waterworn varieties, and especially the more spherical grains, were derived from older sediments, and had undergone at least one previous cycle of erosion. The pink zircons, however, are probably derived from the andesitic rocks which have contributed so largely to the Aure sediments. The relative proportions of pink and colourless zircons varied from rock to rock. Both are scarce in the pyroxene-rich greywackes (Ouka, UK.562, and Dude, UV.381), and in the coarse, gritty greywacke (UK.2623) from the top of the Cupola section, in which the pink variety is dominant. As with the garnets, the zircons are most abundant in the finer-grained Beoke (UK.797) and Murakawarra (UK.789) greywackes. In these two rocks the colourless zircons greatly outnumber the pink zircons, and a large proportion of the colourless zircons are well rounded (more than 50 per cent). In the Napere greywacke (UK.1041) also, the waterworn, colourless zircons predominate. In the coarser grained UK.2636, by contrast, not more than 25% of the colourless zircons are waterworn.

It might appear from the distribution of the zircons and garnet that the proportion of material derived from older sediments and other non-andesitic rocks increases in the finer-sized Aure sediments ; but accessory minerals like zircon are always fine-grained and would, therefore, show a tendency to concentrate in the finer-grained greywackes, regardless of the distribution of the other constituents of the source rocks from which the zircons were derived. This tendency is clearly evidenced by the restriction of the zircons and garnets to the finer fractions of the rocks.

IGNEOUS ROCK FRAGMENTS

The proportion of igneous rock fragments present varies from only 5% for the medium-grained Napere greywackes (UK.1041-1042), up to 30% in the gritty greywackes of the Cupola section (UK.2623, 2625), as indicated in Table 1. In the finer-grained rocks they consist almost wholly of a variety of andesites, and the fragments are, in the main, of a size comparable with the coarser free mineral grains (plagioclase and hornblende). In the coarser-grained rocks, the igneous fragments are often distinctly larger than the mineral grains (Plate XIII, Figs. 5, 6) and include a greater variety of rock types, including granite, syenite(?), diorite, basalt(?) and gabbro(?).

Of the andesite fragments, some are glassy, with only a few microlites, others are porphyritic, with stumpy plagioclase phenocrysts and in some cases hornblende crystals, set in a pale green glass, which is generally unaltered, but in some fragments is devitrified. The majority of the fragments consist of zoned phenocrysts of plagioclase (labradorite grading to andesine) and less numerous phenocrysts of hornblende, set in an intergranular groundmass of felspar laths, iron ore granules, and minute grains of hornblende (Plate XIII, Fig. 3), or else in a fine granular groundmass of quartz and alkali felspar, when they resemble dacites. Others again have phenocrysts of plagioclase only, or less commonly of hornblende only, in a micro- to crypto-crystalline base. Several varieties of andesite can be distinguished according to the nature of the hornblende phenocrysts they contain—those with hornblende pleochroic from straw-yellow to brown, those with hornblende pleochroic from green to brown, and those with hornblende pleochroic from foxy-red to yellow-brown. In many fragments, particularly those with foxy-red hornblende, the hornblende phenocrysts are rimmed with magnetite granules ; and in some instances only the rims remain as pseudomorphs after the original hornblende crystals, proving that the rims develop as the result of a primary or deuteric reaction within the magma.

Fragments of pyroxene-andesite are in the minority, but occur in the greywackes relatively rich in pyroxenes, namely, the Dude (UV.381) and Ouka (UK.562) greywackes, and in the fine-grained conglomerate or pebbly greywacke UV.388 from the Dude section. The pyroxene may occur as individual phenocrysts, or as glomeroporphyritic clusters. In some fragments such clusters of pyroxene crystals occur sporadically through a rock which otherwise consists of plagioclase phenocrysts studded through a microcrystalline base, and it would be possible for such a rock to be broken into fragments which would give the impression of two distinct rock varieties a labradorite-porphyrite, and a pyroxene andesite. Occasionally the pyroxene and plagioclase tend to occur together in glomeroporphyritic clots, and such a clot separated from the groundmass would appear as a fragment of gabbro. The occasional gabbro(?) fragments in the greywackes may be of this character.

The majority of the andesite fragments are fresh, but in every section some of them are weathered, the degree of weathering ranging from cloudiness of the groundmass to complete decomposition of the hornblende and felspar phenocrysts and, in some instances, staining of the whole fragment with limonite. The iron oxide minerals in such weathered fragments are completely altered to leucoxene.

The fragments of igneous rocks other than andesite are relatively uncommon, and often cannot be identified with certainty, because the fragments are too small to be wholly representative of coarse-grained rocks. Some fragments consist of allotriomorphic grains of pyroxene and plagioclase suggesting that they are derived from gabbro.

In UK.2642 a fragment of quartz-diorite with prismatic green hornblende was found, while in UK.2635 occurred fragments of a hornblende-granite (granodiorite?), a syenite (or fragment of granite felspar), a fragment of hornblende-gabbro or diorite, and a fragment of amphibolite-like hornblende. UK.2636 contained a fragment of severely weathered gabbro-like rock, but this may have been a clot of hornblende and plagioclase from one of the andesites. It also contained what appeared to be a fragment of metamorphosed granite in which granulation had occurred along the margins of the individual quartz and felspar crystals.

Fragments of reef quartz occur throughout the series but are more abundant and larger in the gritty rocks and in the pebbly conglomerates (UV.388) where they can be seen in the hand specimens (Plate XII, Fig. 2).

SEDIMENTARY ROCK FRAGMENTS

Under this heading are included sedimentary fragments and fragments of metamorphic rocks presumed to be of sedimentary origin. The proportion of such rocks ranges from as little as 1 per cent in the Napere greywacke to as much as 24 per cent in the gritty sandstones of the Cupola section (Table 1). As with the igneous fragments, the sedimentary fragments approximate in size to the free mineral grains in the finer-grained greywackes, but are notably larger than them in the more gritty rocks. The proportion of sedimentary fragments to igneous fragments varies widely from a ratio of 1 : 13 to 10 : 9, the higher ratios being found in the gritty sandstones of the Cupola section (Table 1).

The rock types represented consist of shales and mudstones, occasionally with enclosed foraminifera closely resembling those found free in the greywackes, quartzites, coarse-grained and fine-grained, grading into cherts, red jasper, chlorite-quartz schists, quartz-sillimanite schist (one fragment only) (UK.2642), a fragment of fibrous green actinolite in quartz (UK.559) biotite-quartz schist or biotite hornfels, sandstone, sometimes with a tendency to ' augen ' structure, a distinctive graphitic quartz schist, with pronounced foliation and often somewhat crumpled, and an occasional fragment of muscovite-schist. The graphitic-quartz schist, and some of the sandstones, which contain graphite, and have undergone a degree of metamorphism, as indicated by the elongation of the quartz grains, bear a considerable resemblance to the few specimens of schists from the Kaindi Series (Mesozoic) available for study.

One small fragment of a garnet-quartz rock was observed in UK.2623 and a (?) chiastolite slate in UK.560.

GRAIN SHAPE

The free mineral grains are highly angular, often with projecting corners (Plate XIII, Figs. 1-4). The felspars tend towards a prismatic form, often truncated by a fracture, and are clearly derived from intratelluric crystals (phenocrysts) of andesitic magmas (Plate XIII, Fig. 2). In the more prismatic forms the long axis is about 1·5 times the length of the short axis, but the ratio ranges up to 6·0 in some fragments.

The hornblende fragments are angular to prismatic, or hexagonal, according to the degree that they have been fractured or resorbed in the magma prior to extrusion. They are clearly derived from the intratelluric crystals of the andesitic magmas represented by the fragments of andesite. The pyroxenes rarely preserve a crystal outline, and show a more spheroidal, though angular, shape with the long and short axes approximating to one another.

The rock fragments, on the contrary, are nearly always well rounded, although they often depart widely from sphericity. The andesitic fragments show a closer approach to spherical shape (Plate XIII, Figs. 2, 3) than the more schistose fragments, but the presence in them of large plagioclase phenocrysts provides cleavage directions of ready fracture, which in some instances have influenced the shape of the fragment and given it an irregular or elongated form.

The schist fragments, and particularly the graphitic schist, are well rounded, but distinctly elongated parallel to the plane of schistosity (Plate XIII, Figs. 4, 5) and tend to lie with their long axes parallel to the bedding of the rock. In general this long axis is 2 to 4 times as great as the short axis, as seen in thin section. When broken out of the rock a number of the coarser schist fragments tend to be irregular, platy fragments, with a smooth and sometimes polished surface.

Quartzite fragments and grains of reef quartz tend to a more spheroidal shape, with long and short axes approaching each other. A number of the grains are rounded at the corners, but as many are angular or subangular (Plate XIII, Fig. 6).

The difference in form of the free grains as compared with the rock fragments is to be attributed to the strong cleavages of the mineral grains as compared with the rock fragments. Most of the mineral grains possess one or more cleavage directions running the whole length of the grain, whereas in the rock fragments, even the most highly schistose, the fine-grained composite texture of the rocks makes for directed attrition rather than fracture along a plane of schistosity. The quartzite fragments, and particularly the reef quartz fragments, tend to coarser granular texture, without schistosity, and so undergo random attrition. This is in keeping with Fischer's (1933) observations on the components of European greywackes. The relation may be expressed as follows.

Component	*Shape* length : breadth	*Angularity*
Felspar	2 : 1	angular
Hornblende	2 : 1	angular
Pyroxene	1 : 1	angular
Biotite	3 : 1	angular
Quartz	1 : 1	angular
Andesites	1·5 : 1	sub-angular to rounded
Reef Quartz	1·2 : 1	sub-angular
Schists	2·7 : 1	rounded

GRAIN SIZE AND DEGREE OF SORTING

Although friable, the majority of the specimens could not be broken down easily into their discrete grains. The finer-grained sediments were disintegrated by first cracking a block of the rock into fragments about 1·0 cm. across, with a chisel hammer, and then repeatedly boiling the fragments in water. Such fragments as did not yield then, on pressing with the fingers, were disintegrated by gentle rolling of the water-saturated fragments with a glass roller on an iron plate.

The coarser-grained and ill-sorted greywaekes were first broken into rather larger fragments, and subjected to similar treatment except that the use of the glass roller was omitted. The few calcified composite fragments that resisted disintegration between the fingers were separated from the sand and broken down by pressure with the flat face of a hammer. Care was taken not to crush the coarser homogeneous particles.

The samples were then supplied in pulp form to the Melbourne Ore Dressing Laboratory, where they were treated with wetting agents and rolled in bottles for 24 hours. The wetting reagents used were :

Samples	UK.2636	Aerosol (Amer. Cyan. Co.)
	UV.381	do.
	UK.797	Perminal W.A. (I.C.I.)
	UK.562	do.
	UK.789	Sodium silicate
	UK.2623	do.
	UK.1041	Aerosol (Amer. Cyan. Co.)
	UK.1040	do.

They were then wet-screened on a 300-mesh screen (British Standard) and the oversize was dried and dry-screened on all screens over 300-mesh. Much of the -300 mesh fraction was finely dispersed, and to facilitate settlement and collection a flocculating agent was added (less than 0·4 gram. of which about half could be expected to precipitate with the dispersed fraction).

Eight samples were sized, the samples being selected so as to represent both the full range in grain size of the rocks that could be described as sandstones or gritty sandstones, and each of the main sandstone horizons of the three field sections represented in the collection. The results obtained are set out in Table 2 and reveal the uniformly ill-sorted character of the greywackes.

SPECIFIC GRAVITIES

The specific gravities of a series of eight specimens, all but one corresponding to those sized, are given in Table 3. The determinations were made on powdered rock in a pycnometer, using 20 gram samples, taken from specimens used in the porosity tests described below, after they had been dried at 110°C. The powders were immersed in distilled water at 10°C in the pycnometer, and then evacuated with a hand pump until no renewed emission of bubbles could be detected on further reduction of the pressure. If compared with the proportions of matrix in the respective rocks (Table 1) it will be seen that the specific gravity decreases as the percentage of matrix increases.

TABLE 3

SPECIFIC GRAVITIES, ADSORPTION RATIOS AND POROSITIES OF AURE GREYWACKES

Rock	Specific Gravity (Samples dried at 110°C.)	Adsorption Ratio	Porosity (dried at 110°C.) %	'Effective Porosity' (natural air-dried condition) %	Remarks
UK. 789 Murakawarra sandstone	2·501	14·5	26·6	16·2	friable, fine-grained
UK.797 Beoke sandstones	2·452	9·23	18·47	—	scaled and collapsed in water. Resembles UV.381, UK.562
UK.562 Ouka sandstone	2·546	9·0	18·6	6·0	compact medium-grained
UK.1042 Napere sandstone	2·411	20·36	32·93	—	friable, medium-grained : fine cracks opened on immersion : portion of block collapsed
UK.2623 Upper sandstone, Cupola section	2·625	10·9	22·3	18·5	friable, gritty
UK.2636 Middle sandstone, Cupola section	2·597	10·3	21·1	11·7	medium-grained
UK.2642 Lower sandstone, Cupola section	2·613	3·0	7·3	3·2	calcified, gritty
UV.381 Dude section	2·571	7·2	15·7	5·1	compact, medium-grained

POROSITIES

The ratios of absorption and the porosities of the same eight specimens are also given in Table 3. In making these determinations, cuboid blocks of the naturally air-dried specimens were broken out of the specimens with a cold chisel and weighed. The individual blocks weighed between 150 grams and 320 grams. They were then immersed in cold distilled water and evacuated with a hand pump until no further emission of bubbles could be detected. The partial vacuum was maintained for one hour, after which the specimens were left immersed at atmospheric pressure for 10 days. The surfaces were then 'blotted' with a dry towel, and the blocks weighed, after which they were dried in an air oven at 110°C to constant weight.

The high porosity recorded for UK.1042 is due partly to the fact that this specimen developed several fine cracks while immersed. Apart from this, however, there is reason to believe that the porosities as measured are in excess of what might be called the ' effective porosity ' of the rocks in their natural state. Thus every specimen weighed less after air-drying at 110°C than in its natural air-dried state. In two of the specimens this arose partly from scaling and collapse of portions of the blocks during immersion, but the other specimens underwent little or no disintegration. Presumably, therefore, this loss in weight arose from a drying out, and shrinkage, of the clay minerals in the matrix of the rock when dried at 110°C.

The porosities were recalculated, therefore, for the six specimens which showed little or no disintegration on immersion, using their weights after immersion, and their weights in a natural air-dried state, prior to immersion, instead of their weights after drying at 110°C subsequent to immersion. The values obtained are entered in Table 3 as ' effective porosities.' In calculating these values the specific gravities used were those of the specimens dried at 110°C, so that some error is introduced here. Since even with air-drying some of the clay moisture must have been lost, it is likely that the effective porosities of the rocks in situ would be still lower than these values.

Several of the specimens, namely, UK.789, UK.2623 and UK.2636, had iron-stained margins. The test blocks were cut so as to exclude these stained margins, but it is possible that the weathering processes that introduced the iron affected the remaining portions, though not sufficiently to be apparent in thin sections. Some change in apparent porosity might have resulted, however.

The low porosity of UK.2642 is a reflection of the abundant carbonate cement in this rock.

CHEMICAL ANALYSES

Chemical analyses of the rocks confirm their unusual composition. Three analyses have been made, one of a calcareous gritty greywacke (UK.2642) from the Cupola section, one of a typical medium grained greywacke from the Napere sandstone (UK.1042), and one of a composite sample of mudstone from three specimens (UK.541, 546, 552) from a horizon between the Beoke and the Ouka sandstones in the Napere Creek section. The analyses were made by Messrs. Avery and Anderson, analytical chemists, and are set out in Table 4, where they are compared with various analyses of greywacke and arkose from other regions.

The outstanding features of the Aure rocks are their uniformly low SiO_2, high MgO and low K_2O contents. Moreover, they are surprisingly similar in general composition, despite the great range in size of the constituent particles of the three rocks. The resemblance between the mudstone analysis and that of the greywacke UK.1042 is surprisingly close.

The composition of the three rocks in terms of their mineral content is masked somewhat by the abundance of calcite in them, present partly as diagenetic calcite, partly as tests of foraminifera. When the analyses are recalculated so as to exlude $CaCO_3$ and hygroscopic water, certain differences between them emerge. These correspond with the petrological characters of the three rocks. Firstly, it is apparent that the allogenic rock material corresponds closely to the composition of average andesite (Table 5), confirming the impression gained from the thin sections, that the bulk of the rocks is derived either from andesitic lavas, or from andesitic tuffs. The gritty greywacke UK.2642 has a distinctly higher SiO_2 content and a lower Al_2O_3 and TiO_2 content than the finer-grained UK.1042 on this new basis. This befits

TABLE 4

CHEMICAL COMPOSITION OF THE AURE GREYWACKES AND MUDSTONES

	UK.1042	UK.2642	UK.541, 546, 552	Archaean Greywacke (av. of 3)	Franciscan Greywacke (av. of 3)	Arkose (Victorian Jurassic) (av. of 3)	Arkose (Triassic)
SiO_2	53·30	52·34	52·36	62·40	69·69	61·98	69·94
Al_2O_3	18·33	12·44	15·83	15·20	13·53	16·89	13·15
Fe_2O_3	2·41	1·23	1·96	0·57	0·74	1·68	2·48
FeO	2·36	3·02	3·74	4·61	3·10	3·56	—
MgO	2·62	2·54	3·00	3·52	2·00	1·92	tr.
CaO	5·88	12·80	5·91	4·59	1·95	2·23	3·09
Na_2O	2·18	2·04	2·18	2·68	4·21	3·00	5·43
K_2O	1·72	1·56	1·50	2·57	1·71	1·65	3·30
H_2O above 105°C	3·14	0·96	3·62	1·56	2·08	3·37	1·01
H_2O below 105°C	5·74	1·31	5·08	0·07	0·26	2·34	
CO_2	1·00	8·78	3·34	1·30	0·23	0·58	—
TiO_2	0·84	0·62	0·91	0·50	0·40	0·68	—
P_2O_5	0·28	0·19	0·24	—	0·10	0·22	—
MnO	0·08	0·23	0·08	—	0·01	0·13	0·70
SO_3	0·08	tr.	0·04	—	—	—	—
Cl	0·03	0·03	0·03	—	—	—	—
	99·99	100·09	99·82	99·57	100·01	100·23	99·10

UK.1042 Medium-grained greywacke, Napere sandstone, Napere Creek section.
UK.2642 Gritty greywacke, lower sandstone, Cupola section.
UK.541, 546, 552 Composite samples of mudstone from between the Beoke and Ouka sandstone horizons, Napere Creek Section.

Analyst : Avery and Anderson.

TABLE 5

COMPOSITION OF AURE GREYWACKES AND MUDSTONE CALCULATED FREE OF $CaCO_3$ AND HYGROSCOPIC WATER

	UK.2642	UK.1042	UK.541, 546, 552	Average Andesite (Daly)	Average Augite Andesite (Daly)	Average Hornblende Andesite (Daly)
SiO_2 ..	63·81	57·72	59·25	59·59	57·50	61·12
Al_2O_3 ..	15·17	19·85	17·91	17·31	17·33	16·10
Fe_2O_3 ..	1·50	2·61	2·22	3·33	3·78	2·89
FeO ..	3·68	2·55	4·23	3·13	3·62	2·40
MgO ..	3·10	2·83	3·40	2·75	2·86	2·44
CaO ..	5·88	5·39	3·25	5·80	5·83	5·80
Na_2O ..	2·49	2·36	2·47	3·58	3·53	3·83
K_2O ..	1·90	1·86	1·70	2·04	2·36	1·72
H_2O ..	1·17	3·40	4·09	1·26	1·88	1·43
TiO_2 ..	0·75	0·91	1·03	0·77	0·79	0·42
MnO ..	0·28	0·09	0·09	0·18	0·22	0·15
SO_3 ..	tr.	0·09	0·05	—	—	—
Cl ..	0·04	0·03	0·03	—	—	—
P_2O_5 ..	0·23	0·30	0·27	0·26	0·30	0·15
$Na_2O : K_2O$	1·30	1·27	1·45	1·75	1·50	2·22

the notable number of pellets of graphitic schist and quartzite contained in it. The higher MnO and the unchanged MgO contents (relative to the other two rocks) is probably due to some introduction of $MnCO_3$ and $MgCO_3$ during diagenesis, for which no allowance can be made in calculating the results on a carbonate-free basis. The slightly higher CaO, Na_2O and K_2O contents as compared with UK.1042 argues a slightly higher overall felspar content in UK.2642 as compared with UK.1042, despite the much greater proportion of free felspar grains in UK.1042 (Table 1). The ratio CaO : Na_2O and the ratio Na_2O : K_2O vary only slightly for both rocks, which supports this contention. The extra felspar in UK.2642 is supplied presumably by the igneous rock fragments.

The mudstone, like UK.2642, is slightly higher in SiO_2 and poorer in Al_2O_3 than the medium-grained greywacke UK.1042. It is also somewhat richer in MgO, but is distinctly poorer in CaO than UK.1042. The CaO : Na_2O is only 1·3 as against 2·3 for the two greywackes, indicating that much less plagioclase felspar went to the make up of the mudstones, or else that the plagioclase and hornblende in these rocks have been more completely replaced by calcium carbonate than in the coarser grained rocks. The Na_2O : K_2O ratio, by contrast, is not significantly different from that of the greywackes. Since the K_2O of the original andesites would reside chiefly in their groundmasses, as would much of the Na_2O, there is a suggestion that the greywackes are built largely from the phenocrystic elements of a series of andesites or andesite tuffs, an interpretation supported by their appearance in thin section, whereas the mudstones appear to be formed chiefly from the groundmass constituents of the source rocks. The higher silica and lower alumina of the mudstone may indicate a degree of admixture with fine quartz from ground-up shales or graphitic schist of the terrain, or may simply mark the somewhat more acidic composition of the andesite groundmass as compared with the phenocrysts.

It is also apparent that the matrix of the greywackes which constitutes up to 60 per cent of the rock by micrometric analysis, and not less than 30 per cent by the sizing analyses, must be closely similar in composition to the mudstone, or else the analyses of the three rocks would show greater divergence. In other words, the matrix of the greywackes is " occluded' mudstone, and is a primary matrix, not a product of infiltration during compaction and lithification. This accords with the petrographic evidence, and with the results of the sizing analyses.

The other fact emerging from the analyses is the small amount of material that could have been contributed by rocks other than andesites or andesitic tuffs. It is particularly apparent that fine-grained sediments of the normal type, that is, shales or mudstones relatively rich in potash, were not exposed to any great extent in the terrain supplying the detritus. Had such sediments contributed to the Aure rocks, their contribution would have been marked by a distinct increase in the K_2O content of the mudstones relative to the greywackes, such as was found for example in the mudstones associated with thick arkose formations in the Jurassic of Victoria (Edwards and Baker, 1943). These were derived from a terrain consisting chiefly of granitic and dacitic rocks on the one hand, and Palaeozoic sandstones and mudstones (carrying up to 5·0% K_2O) on the other hand. The granitic debris was concentrated in the arkoses, whereas the mudstone debris was concentrated in the Jurassic mudstones, rendering them distinctly richer in potash than the arkoses.

There is a distinct possibility, however, that a proportion of the sedimentary rocks exposed in the Papuan terrain were older greywackes, not greatly different in composition from the rocks under discussion.

Origin of the Greywacke

It is clear that the greywackes were derived from predominantly andesitic rocks, although the consistent occurrence of grains and pebbles of rocks such as graphitic schist, mica schists, quartzites, jaspers and shales, particularly in the coarser-grained members, establishes that rocks of this nature were exposed in the Miocene terrain. So also the occurrence of occasional pebbles and cobbles of granite, syenite, quartz diorite, hornfels and reef quartz establishes the presence of rocks of these types in the terrain, while the occurrence of rounded pebbles and cobbles of andesites establishes the presence of andesite lava flows. It seems probable, however, that the bulk of the sediments were derived from andesitic tuffs, rather than from lava flows. The felspar and ferromagnesian grains in the greywackes closely resemble the plagioclase and ferromagnesian phenocrysts of the andesitic lavas, as represented by the igneous fragments in the greywackes, but if they were derived from lava flows it is necessary to picture the erosion of the andesites operating so as to free the felspar and hornblende phenocrysts without permitting them to weather. Such a process is difficult to visualise in a tropical region where, under present conditions, all rock above ground water level is deeply weathered, in striking contrast to the rocks at or below the water table, which are preserved in a perfectly fresh state. Erosion of massive rocks under such conditions would be most unlikely to yield coarse grains of fresh plagioclase and hornblende ; and such evidence as is avilable suggests that the climate prevailing in New Guinea in the Miocene was little different from that prevailing at present. Abundant rainfall is indicated by the abundance of wood fragments in the sediments. The presence of a tropical turtle (*Carettochelys*) points to a warm, if not tropical, climate, and this finds some support in the occurrence of corals, despite the unfavourable conditions for their growth that would attend rapid deposition. Relatively unconsolidated tuffs, however, would be subject to rapid erosion, and felspar phenocrysts in the tuff fragments would be freed readily by attrition of the small, perhaps incoherent, fragments during transport, if they did not occur free originally, as in crystal tuff.

This raises the possibility that the greywackes are simply marine tuffs, deposited in situ, by showers of ash from a series of contemporary island volcanoes, such as now enclose the Bismarck Sea. A number of features of the rock are, however, opposed to such an interpretation.

The poor sorting and the graded bedding which characterize the sediments can only indicate a continuous addition of sediments to a region of still and moderately deep water (within the limits of the neritic zone). Settling of sediment in still water would lead to excellent sorting if the addition of sediment was pulsatory or spasmodic. With continual addition, however, slow settling clays or other fine materials would be intermingled with faster settling coarser material added later. Any interruption in the addition of coarse sediment would result in the development of a horizon of mudstone. If sedimentation was completely arrested, then on renewal of sedimentation, a horizon of well-sorted grit or sandstone might well develop immediately above the mudstone horizon. No such well-sorted sandstone horizons have been noted in the course of exploration of this part of Papua ; and it may be assumed that they are not common, if they occur at all. It is concluded, therefore, that sedimentation proceeded by a continuous addition of mud or clay, with an intermittent addition of coarser material—sand, grit, pebbles and cobbles—to the basin of deposition. Weak bottom currents played some part in the accumulation of the beds of sandy shale or mudstone, since these rocks frequently exhibit fine current bedding. Presumably such currents as operated were too weak to move sandstone grains, but were strong enough to move fine particles to some degree and so aid their local accumulation.

In the light of this, the composition of the mudstones—their obvious derivation from andesitic material—is significant. It seems improbable that several thousands of feet of tuff would be deposited over an area some hundreds of square miles in extent without repeated interruptions in volcanic activity. Moreover, the consistent occurrence of wood fragments along bedding planes would argue some interruptions in sedimentation. During periods of quiescence, erosion would continue on the adjacent land surface, and might be expected to yield detritus of different composition to the greywackes—either normal potassic mudstones or arenaceous sandstones. Neither rock types have been detected, though it must be admitted that the study of the mudstones has been very limited. If, however, the land surface was largely blanketed with andesitic tuffs, the variations introduced by periods of volcanic quiescence would be negligible. It may be noted, in this connection, that Mr. Montgomery, of the Australasian Petroleum Company, considers that he can detect fluctuations in the relative proportions of heavy minerals of sedimentary origin and andesitic origin in different horizons of greywackes in the Maropa section of the Aure trough (personal communication). How far these fluctuations are significant may be questioned in view of the variations of heavy mineral content with grain size of the rock noted herein.

The poor sorting of the sediments argues against their deposition as in situ tuffs in that the combined action of aerial and water sorting, coupled with periodic vulcanicity, should give rise to well-sorted sediments. The efficacy of aerial sorting is indicated by Wentworth's (1928) studies of tuffs at Oahu, where he found that a high degree of sorting of sand size grains was developed in tuffs that fell only several thousands of feet from their source. Moreover, it seems unlikely that large quantities of coarse and fine material would normally be projected equally over the distances involved in the Aure trough.

Another feature of the rocks at variance with the idea that they are marine tuffs deposited in situ is the highly assorted variety of rock fragments present in them. Successive showers of tuff from a particular volcano would be expected to contain a limited variety of andesites, if not only one variety, and a limited variety of extraneous rock fragments (accidental fragments) derived from the terrain through which the volcano erupted. Yet nearly every thin section contains three to six varieties of andesite fragments and several varieties of sedimentary rock fragment. It is true that certain greywacke formations (the Ouka sandstone, and the Dude sandstone) are characterized by an abundance of pyroxenes, not found in other greywackes examined, and also by fragments of pyroxene andesite, indicating that they were derived either from tuffs which included a high proportion of pyroxene-andesite tuff, or from volcanoes containing pyroxene-andesite magma ; but these greywackes also contain the same varieties of hornblende andesite and sedimentary rocks found in the other greywacke formations.

The grain shape of the rock fragments also is significant. The andesite fragments, and in particular the sedimentary fragments (schists), are mostly well-rounded fragments. If they were simply accidental material torn up from the terrain during a volcanic outburst, it might be expected that a high proportion of such fragments would be angular. The fact that they are so well rounded suggests attrition during transport, presumably in running water. The angularity of the free mineral grains can be attributed to their splitting along their prominent cleavages during vigorous transport by running water. If they were simply erupted from a volcano into water, a higher proportion of them might be expected to retain their crystal outline.

Yet another feature favouring derivation by normal erosion processes from previously deposited terriginous tuffs is the constant presence, in every slide, of a proportion of weathered mineral grains and rock fragments, which, in view of the unweathered state of the greywackes, were weathered before deposition. Such weathering could be attributed to weathering of tuff surrounding a volcanic cone, with re-eruption of the cone material in later outbursts; but such a sequence of events might be expected to give rise to weathered fragments and grains in localized greywacke formations, and not throughout the series as a whole.

The distribution of the gritty or pebbly greywackes is also difficult to account for if the sediments are regarded as original tuffs. These coarser grained rocks occur both as thick beds, and as isolated pockets with a volume of only a cubic yard of so, in otherwise pebble-free greywacke. It has been suggested that the isolated pockets owe their pebbles to material carried down attached to uprooted trees, whereas the thick beds mark floods. If the rocks are thought of as tuffs, the isolated pockets of ill-sorted pebbles, which include a highly mixed assortment of rock types, are difficult to explain.

For these various reasons it is concluded that, though a portion of the sediment may have been added as air-borne volcanic tuff, the bulk of it has been derived from the rapid erosion of relatively unconsolidated terriginous andesitic tuffs, with thin intercalated andesite lava flows. The tuffs are pictured, moreover, as blanketing the earlier terrain to such an extent that little of the basement complex was exposed to erosion. There is also a possibility that a proportion of the sediments forming the basement complex were older greywackes, or tuffs, not greatly different in composition from those under discussion (Carey, 1945).

CONDITIONS OF DEPOSITION

The abundance of woody fragments point to deposition relatively close to a land margin, while the great thickness of sediments involved indicates either deposition in deep water, or in an area with a subsiding floor. The occasional presence of shell beds and corals suggests the latter. The graded bedding indicates that the sediments were deposited in still water, free from all but weak bottom currents over most of the area, and that the addition of sediment was in some degree periodic or intermittent, as regards the supply of coarse detritus. The addition of fine detritus, however, appears to have been continuous. Such variations presumably reflect some seasonal variation in the run-off of the rivers bringing sediment to the basin of deposition.

The unstable character of the chief constituents of the sediments points to rapid erosion, while the angular nature of the mineral grains suggests vigorous transport. The relatively coarse size of the felspar grains—that is, when compared to the phenocrysts in the andesites—suggests that the transport distance was short. The absence of weathering in the rocks as a whole is attributed simply to their deposition in water, which would effectively seal them from chemical weathering, other than such diagenetic processes as carbonatisation, which has operated freely. The development of iron sulphides in a number of the rocks can be attributed to the decomposition of the enclosed foraminifera. The lack of sorting implies that the sediments were discharged after a short journey, directly into moderately deep (within the limits of the neritic zone), still water. Presumably, therefore, the sediment was derived from a mountainous, forested region, traversed by short, vigorous rivers, not greatly different in aspect from the mountainous parts of present-day New Guinea. The climate was warm or tropical, and the rainfall abundant.

Nomenclature

It is now appropriate to discuss the classification of the Aure sediments. In classifying sedimentary rocks it is essential to distinguish between the processes of sedimentation, which are *universal factors*, in that whenever and wherever they operate, they tend to produce the same class of sedimentary rock, and *regional factors*, such as the composition, hardness or grain size of the rocks on which the sedimentary processes operate, which are fortuitous, and which tend only to introduce modifications within the class of sediments produced. The name given to a sediment should imply a manner of attrition, a degree of attrition, a mode of transport, and a mode of deposition. The term *tuff* is an excellent example, in that it implies all these factors of process and is independent of such fortuitous factors as the composition of the resultant sediment or of the source rock. These, being closely linked, can be expressed by a modifying term, as andesitic-tuff. By contrast, the term *arkose*, with its emphasis on the mineral composition of the source rock and the resultant sediment, is much less satisfactory, in that arkose as commonly defined (Wentworth, 1932) gives a vague and confused picture of the conditions attending the formation of such rocks and puts undue stress on the importance of extremes of climate.

The importance of processes of sedimentation as a basis for classification of sediments is particularly apparent in naming the Aure sediments. If they are simply volcanic ash projected into the sea, they are a variety of tuff. Wentworth and Williams (1932) define the term *tuff* as indicating ' compacted fine volcanic ashes and dust, whether pure or admixed with sediment. Should the amount of sediment exceed that of volcanic ejecta, such terms as tuffaceous sand, tuffaceous clay and tuffaceous sandstone may be used ; if the reverse should be the case, such terms as sandy tuff, clayey tuff—the less important constituent always being used adjectivally.' Tuffaceous sandstone, so defined, refers to a particular variety of the class of sediments embraced by the older term *tuffite*, introduced by Mügge (1893) to indicate a sediment composed of an admixture of volcanic ash and material of non-volcanic origin. Bailey (1926) however, defines tuffaceous sandstone as an epiclastic volcanic rock, composed of volcanic material wholly or in part, which has been transported and redeposited by water, provided its constituent grains lie chiefly between the sizing range of 0·05 to 0·5 mm. It will be clear that if the Aure sediments are regarded as pyroclastics, the use of the term tuffaceous sandstone, whether in the sense of Wentworth and Williams, or that of Bailey, is a misnomer, and should be discontinued. If a more precise name than tuff is required, to indicate deposition in the sea, the term *sedimentary tuff* might be employed. This term is suggested by Wentworth and Williams (1932) for a ' tuff containing a subordinate amount of sediment introduced either during or after deposition.' This may be intended to imply deposition in water, but the definition is not specific on this point. Twenhofel (1932) recognises as sediments ' the material ejected from volcanoes . . . if their temperatures at the time of deposition are sufficiently low not to be important factors in consolidation.' Moreover, he accepts air as a medium in which sedimentation may operate. The more precise, older definition of Walther and Schirlitz (1886) is to be preferred. They define the term (sediment-tuffe) as meaning tuffaceous material projected into water from subaerial volcanoes and there admixed with sediment, in contradistinction to *trocken-tuffe*, laid down subaerially, *wasser-tuffe*, resulting from eruptions under water, and *transport-tuffe* laid down on land, and later removed and redeposited by running water (tuffaceous sandstone of Bailey). A more complete description would be afforded by the compound term *marine andesitic tuff* (as distinct from *submarine tuffs* for the equivalent of wasser-tuffe).

If, however, as suggested in the previous section, the Aure sediments were formed by the erosion of tuff that had been previously deposited on a land surface, the basis for nomenclature is changed. The rocks could be called tuffite, transport-tuffe, or tuffaceous sandstone (in the sense of Bailey), but such terms emphasize the nature of the source rock at the expense of the processes of sedimentation, which are virtually ignored.

If the emphasis is placed on the processes of sedimentation, then the conditions attending deposition, the abundance of fresh angular fragments of chemically unstable minerals, and the extremely ill-sorted character of the sediments, establish that the Aure sediments belong to the class of sediments that has been described by Fischer (1933) as ' poured-in ' sediments (*Einschütt sedimente*).

The characteristic rock of this group of sediments with a grain size comparable to that of the Aure sediments is the *greywacke*. Some disagreement exists as to the precise meaning of this term. Thus Wentworth (1932), following Fay (1920), defines a greywacke as :

> ' a variety of sandstone composed of material derived from the disintegration of basic igneous rocks of granular texture . . . (and containing) . . . abundant grains of biotite, hornblende, magnetite, etc. . . . (It is) the ferromagnesian equivalent of arkose.'

Twenhofel (1939) also, is of this view :

> ' greywacke is defined as the basic equivalent of an arkose, and is composed of little decomposed particles derived from basic igneous rocks and their metamorphic equivalents, thus having a large content of ferromagnesian minerals.'

More recently, Pettijohn (1943) has reviewed chronologically the numerous descriptions of greywackes since the introduction of the term in 1808, and emphasises the fact that the definition of greywacke as ' a basic equivalent of arkose ' does not fit any of the many greywackes described by field workers in the past 150 years. He shows, moreover, that greywacke, as originally defined, connotes a distinct type of sandstone, of world-wide occurrence, characterized by the following features :

> ' (1) large detrital quartz and felspar (" phenocrysts ") set in (2) a prominent to dominant " clay " matrix (and hence absence of infiltration or mineral cement) which may on low-grade metamorphism (diagenesis) be converted to chlorite and sericite and partially replaced by carbonate, (3) a dark colour (4) generally tough and well indurated, (5) extreme angularity of the detrital components (microbreccia), (6) the presence in smaller or larger quantities of rock fragments, mainly chert, quartzite, slate or phyllite, (7) certain macroscopic structures (graded bedding, intraformational conglomerates of shale or slate chips, slip bedding, etc.), and (8) certain rock associations (as with greenstones) '.

The close resemblance of the Aure sediments to such a sandstone will be apparent.

Pettijohn emphasises the association of graded bedding with greywackes, and the absence of current bedding and ripple-marking in them ; and he relates this characteristic to the conditions under which they are deposited, quoting Bailey (1930, 1936) as to the significance of graded bedding ;

> 'current-bedding and graded-bedding are the distinguishing marks of two different sandstone facies. Current-bedded sandstones are obviously the products of bottom currents. Graded-bedded sediments are the products of settling though comparatively still bottom water, which allows sand and mud to accumulate in one and the same locality, though with a lag on the part of the mud, determined by its finer texture . . . Thus current-bedded sandstones belong to relatively shallow water (or to the air), and graded-bedded sandstones belong to relatively deep water.'

In his emphasis on lack of sorting as a characteristic of greywackes, Pettijohn follows Fischer (1933). Fischer suggests that there are two main classes of sediments (a) sandstones, with adequate sorting and (b) wackes, with little or no sorting ; and he suggests division of the wacke class into clay-wackes, sand-wackes and gravel-wackes, etc., to cover range in grain size. Fischer considers that sediments of the wacke class are indicative of a special tectonic environment attending periods of orogenesis. He notes also that the components of sediments are of two chief types, *stable* components, such as quartz, rutile, zircon, which resist chemical weathering, and *labile* components, such as felspar, hornblendes, pyroxenes, which are subject to chemical weathering ; and according to the proportion of stable and labile components present, he further subdivides wackes as follows :—

more than 90% stable - - - quartz-wacke
90%-66% stable - - - - - quartz-meng-wacke
less than 66% stable - - - - meng-wacke

Since the most common labile component of sediments is felspar, the existing term greywacke seems adequate to describe both quartz-meng-wackes and meng-wackes ; the new term quartz-wacke seems desirable, however, for the purely arenaceous members of the wacke class.

It will be clear that, with the origin ascribed to them in the previous section, the Aure sediments are greywackes in the sense of Pettijohn and Fischer, which is accepted here as the correct interpretation of the term, and that they constitute meng-wacke in the special sense of Fischer. They range in grain size from meng-clay-wackes to meng-gravel-wackes, with meng-sand-wackes (greywackes) prevailing.

The obvious derivation of the Aure greywackes from tuffs makes them appear abnormal, but there is a possibility that many greywackes owe some of their features to the presence of relatively unconsolidated tuffs in the terrain from which their components were drawn. Pettijohn and others have emphasised the frequent association of the older greywackes with greenstones, and it seems possible that the labile components of such greywackes might have been derived from the rapid erosion of tuffs associated with the greenstones. If this should prove correct, then the Aure greywackes are unusual only in that they consist of rather more material derived from tuffs, and less material derived from non-volcanic sediments and other rocks than is usual. This is a purely regional and fortuitous difference.

It is perhaps convenient to consider here the differences between greywacke and arkose. Pettijohn draws two distinctions :

(a) greywackes are characteristically graded-bedded ; arkoses are characteristically current-bedded. On Bailey's view, these are the distinguishing features of deep and shallow-water sediments, respectively.

(b) greywackes have a primary clay matrix whereas the matrix of arkoses is a secondary cement, resulting from infiltration during diagenesis. This means that the lack of sorting in arkoses is more apparent than real.

The writer's limited experience of greywackes and arkoses conforms to these observations, but not all arkoses would fit Pettijohn's distinctions, because of the wide range of conditions under which rocks conforming to existing definitions can accumulate. The existing definitions are particularly unsatisfactory in their emphasis on climatic controls to preserve the labile components. Sufficient evidence has accumulated to prove that extensive deposits of arkose can form under both humid tropical and temperate conditions of climate, and that the factors preserving the labile components are rapid erosion and burial, or submergence (Reed, 1928 : Krynine, 1935 : Taliaferro, 1943 : Edwards and Baker, 1943).

Arkose (excluding so-called ' untransported or sedentary arkoses ') then, like greywacke, requires an environment in which erosion, transportation and deposition are so rapid that complete chemical weathering of the labile components does not take place. This in turn implies a high land subject to vigorous erosion. The differences between the two rocks arise only when deposition begins. If the sediment is deposited under still conditions and not further disturbed, a greywacke results ; if bottom currents separate the clay from sand size particles with or without the development of perfect sorting of the sand size particles, arkose will be formed. Compaction will not change the greywacke notably, but in the case of the arkose the connate waters of the associated mudstones, with their dissolved or suspended material will infiltrate the arkose, and provide it with a fine matrix or cement.

One possible objection to the use of the term greywacke for the Aure sediments is that some authors restrict the use of the name to ancient sediments. However, as Fischer points out, once the relationship of greywackes to processes of sedimentation is recognised, there is no ground for excluding a sediment from the class, simply because of its relative youthfulness.

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Explanation of Plates

Plate XII

Fig. 1. Intraformational Conglomerate, showing a well-rounded pebble of mudstone in a matrix of coarse greywacke. UK 1044. ×1.

Fig. 2. Fragments of pebble-conglomerate from Dude section, UV 388, showing characteristic shape of rock fragments —angular reef quartz, rounded elongated schist, rounded or sub-angular andesite. ×1.

Plate XIII

Photomicrographs

Fig. 1. Graded bedding in fine-grained greywacke. The photograph shows the full thickness of one bed overlain by the bottom of another. UK 797. ×18.

Fig. 2. Micro-breccia texture in a medium-grained greywacke, showing fragments of andesite. (Nicols half-crossed. UK 2644. ×18.

Fig. 3. Texture of medium-grained greywacke with a high proportion of matrix (50 per cent or more), showing a rounded fragment of hornblende andesite, and a rounded fragment of quartz schist (white). A zoned plagioclase, partly replaced by grey calcite, can also be seen. UK 1042. ×18.

Fig. 4. Texture of coarse-grained greywacke, showing rounded fragments of schist and shale, and portion of a fragment of hornblende andesite. UK 2636. ×18.

Fig. 5. Rounded, elongated schist fragment, and rounded shale fragment in a coarse-grained gritty greywacke. UK 2642. ×18.

Fig. 6. Rounded shale fragment and sub-angular quartzite fragment in a coarse-grained gritty greywacke. UK 2645. ×18.